Renewable and Sustainable Energy Reviews 32 (2014) 504–512

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Bioenergy potential from crop residue biomass in India

Moonmoon Hiloidhari [a,1], Dhiman Das [b], D.C. Baruah [a,*]

[a] Energy Conservation Laboratory, Department of Energy, School of Engineering, Tezpur University, Tezpur 784028, Assam, India
[b] School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 4 January 2012
Received in revised form
4 December 2013
Accepted 4 January 2014
Available online 1 February 2014

Keywords:
Bioenergy
Crop residue
Surplus biomass
Spatial assessment

ABSTRACT

Biomass based energy generation is one of the major focus areas of renewable energy programs in India. The strength of India's biomass resources mostly lies in the agricultural sector. A large quantity of crop residue biomass is generated in India. However, crop residue biomasses are distributed resources with variation in spatio-temporal availability and its characteristics. Competing uses of residues also vary geographically. Therefore, local biomass databases are important for decentralized bioenergy programs. However, in India, state wise crop level biomass database is limited. The present paper assessed crop residue biomass and subsequently bioenergy potential in all the 28 states of India using crop statistics and standard procedure. A total of 39 residues from 26 crops cultivated in India are considered for the study. Overall, India produces 686 MT gross crop residue biomass on annual basis, of which 234 MT (34% of gross) are estimated as surplus for bioenergy generation. At state level, Uttar Pradesh produces the highest amount of crop residue amongst all the 28 states. Amongst all the crops, sugarcane produces the highest amount of surplus residue followed by rice. The estimated annual bioenergy potential from the surplus crop residue biomass is 4.15 EJ, equivalent to 17% of India's total primary energy consumption. There exists variation from 679 MJ (West Bengal) to 16,840 MJ (Punjab) of per capita crop residue bioenergy potential amongst the states of India. The information generated in this study is expected to be useful for decentralized crop residue based energy planning by the states of India which in turn would positively influence the overall renewable energy growth in India.

Contents

* Corresponding author. Tel.: +91 94355 08563; fax: +91 3712 267005.
E-mail address: baruahd@tezu.ernet.in (D.C. Baruah).
[1] Current address: Institute of Transportation Studies, University of California, Davis, CA 95616, USA.

1364-0321/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2014.01.025

1. Introduction

1.1. India's energy concern and growth of renewable energy

Improving living standard, economic and industrial expansions, population growth has possess serious challenges on India's energy sector. Although the country is recognized as one of fastest growing economies of the world, basic energy needs of thousands of millions of its citizens are yet to be fulfilled. It is reported that by 2031–2032, power generation capacity must increase to nearly 800 GW from the current capacity of around 183 GW, inclusive of all captive plants to meet the basic energy needs of its citizens [1]. Taking a historical prospective, Kumar and Jain [2] reported that during 1970–71 to 2006–07, coal consumption in India has increased from 71.2 MT to 462.7 MT, crude-petroleum consumption has gone up from 18.4 MT to 146.5 MT and the natural gas consumption rose from 0.64 Giga cubic meters (GCM) to 31.36 GCM. Similarly, electricity consumption has also increased from a level of 43.7 TWh to 443.1 TWh during the same period.

Contrary to the demand, native energy reserves of India are not adequate and therefore, the country is fairly dependent on foreign imports of oil. For instance, against the consumption of 161 MT crude oil in 2008–09, indigenous production was only 34 MT [3]. India imports nearly 80% of crude oil. Similarly coal and LPG are also imported to meet the domestic demand. Major portion of coal produced in India is used for electricity generation (almost 54% of electricity generation is based on coal fired power plants). Other energy options like, large hydro and nuclear power projects are facing serious environmental criticisms and beleaguered with problems. Thus, there is a serious energy supply–demand imbalance in the country. Demand for electricity has also exceeded supply with improving living standard. The electricity supply constrain has forced almost all the sectors-industrial, commercial, institutional or residential to rely on diesel or furnace oil. Lack of adequate rural electricity supply has been leading to large scale use of kerosene. About 78 million people in India mainly depend on kerosene for lighting [4].

Growing energy demand coupled with limited conventional fuel options, geo-politics of oil and environmental concern has compelled India to search for renewable and sustainable energy options. Biomass, solar, wind and small hydro have been identified as the thrust areas of renewable energy development in India. The estimated grid-connected power potential together from biomass, wind and small hydro in the country is more than 87 GW. Similarly, solar potential ranges in between 20 and 30 MW/km^2 [5]. Biomass resources are relatively uniformly available in India compared to other renewable sources. Realizing the potential of bioenergy generation, the Ministry of New and Renewable Energy (MNRE), India has initiated several biomass programs, with encouraging degree of success.

1.2. Existing status of bioenergy uses in India and needs for future planning

1.2.1. Traditional uses of biomass

Although accesses to electricity and LPG have been improved in India compared to the last few decades, consumption of biomass as traditional fuel also increases in parallel and it dominates the fuel mix of rural households. Bhattacharya [6] reported that 64% rural households in India rely on firewood for cooking and another 26% rely on crop residue or animal wastes. Further, in the urban sector almost 30% households rely on traditional energy for cooking. On a comparative study of household energy uses pattern in India and China, Pachauri and Jiang [7] reported that at an aggregate level, solid fuels (traditional biomass and coal) comprise 80% of total residential energy use in both the countries. Large scale use of firewood as cooking fuel is reported in India. Annually about 220 MT of firewood is utilized for cooking in the rural sectors of India [8]. Firewood contributes the major portion of final energy consumption with a variation between 65% and 80% depending on income level of households [9]. Apart from household uses, biomass is also extensively used in various traditional and rural enterprises such as brick making, rice par-boiling, hotel, restaurants, bakeries, potteries and charcoal making [8].

1.2.2. Modern uses of biomass

The modern uses of biomass take the advantages of modern biomass conversion technologies (combustion, pyrolysis, gasification, fermentation, and anaerobic digestion) for production of heat and electricity, liquid and gaseous transportation fuel, biogas for cooking *etc*. There is a huge potential for modern uses of biomass energy in rural India, especially in the cooking and lighting sectors. Balachandra [10] advocated several points in favor of adopting modern biomass energy, especially for rural India *viz*., (i) biomass resources potential in India is high to produce adequate amount of modern energy, (ii) advanced biomass energy technologies for decentralized utilization in rural areas have reached near commercialization, (iii) India has local expertise in developing and deploying biomass gasifier technologies for power generation and bio-methanation technologies for biogas production, (iii) CDM potential is also significant, and (iv) scopes for medium, small and micro scale rural enterprises are large which would help to promote rural income generation and employment.

As per the MNRE (Ministry of New and Renewable Energy, GoI), a total of 288 biomass power and cogeneration projects aggregating to 2665 MW capacity have been installed in the country for feeding power to the grid. The common biomass feedstock for power generation in India includes sugarcane bagasse, rice husk, straw, cotton stalk, coconut shells, soya husk, coffee waste, jute wastes, groundnut shells, saw dust *etc*. A variety of biomasses have been tested for bioenergy generation including woody biomass [11] and loose biomass such as rice husk [12], cashew nut shell [13], areca nut [14], sugarcane residue [15]. Village level decentralized biomass power generation of kilowatt scale has also been commissioned in the country. In a recent study, Dasappa et al. [16] reported deployment of six biomass gasifier based power plant projects with total installed capacity of 0.88 MW in Tumkur district of Karnataka.

1.2.3. Need for crop residue based renewable energy planning

Being an agriculturally dominant nation, the strength of India's bioenergy programs mostly lies in the agricultural sector. Agriculture is regarded as the backbone of India's economy. Although agriculture contributes only 17% to India's GPD, it is the source of subsistence for nearly 60% of its population. About 60% of land area of the country is under various agricultural practices [17]. The arable land in the country is 159 million hectare (Mha), 11.2% of global share. Globally India ranks first in the production of jute and second in rice, wheat, sugarcane, cotton and ground nut. Thus, because of the agricultural strength of the country, crop

residues production in the country is also huge. However, due to the diversity in cropping practices and agro-climatic conditions across the India, distribution and availability of residues is highly spatio-temporal in nature. Although national level estimate of crop residue biomass potential in India is available, state level database is limited, except for a few states [18–21]. Since bioenergy projects are generally of small scale and targeted mainly for decentralized utilization to meet local energy demand, therefore, national estimates may not be adequate for state or local bioenergy planning. Identifying this gap, the present paper investigates and discusses crop residue biomass and subsequently bioenergy potential in all the 28 states of India. Altogether 26 crops generating 39 residues cultivated in different states of the country considered for the assessment. Prospects and possible hurdles of crop residue based bioenergy programs are also discussed highlighting major issues including spatially varying competitive uses of crop residues.

2. Methodology

Crop statistics of India, available from the Ministry of Agriculture (MoA), Govt. of India is a major data source for estimation of crop residue biomass availability [22]. The MoA has adopted a reliable and scientifically robust procedure to derive relatively precise estimation of crop production, cropping area, and yield. Average crop statistics of five years (2003–04 to 2007–08) are used in order to minimize yearly fluctuation in crop statistics.

2.1. Selection of crops

As mentioned earlier, 39 residues from 26 crops are considered and grouped them into following six categories.

(i) Cereal: rice, wheat, maize, bajra, barley, small millet, jowar, and ragi.
(ii) Oilseeds: mustard and rapeseed, sesame, linseed, niger, soyabean, safflower, sunflower, and ground nut.
(iii) Pulses: all types of gram *viz*., black gram, red gram, pigeon peas and lentil.
(iv) Sugarcane.
(v) Horticultural: coconut, banana and areca nut.
(vi) Others including cotton and jute.

Types of residue (straw, stalk, husk *etc*.) and their respective RPR (residue production ratio) and heating values are given in Table 1 for all the selected crops.

2.2. Estimation of crop residue biomass potential

Crop residue is by-product of crop production system. Gross residue potential is the total amount of residue produced while surplus residue potential is the residue left after any competing uses (such as cattle feed, animal bedding, heating and cooking fuel, and organic fertilizer). The surplus fraction can be used for bioenergy generation. Standard procedure is followed to estimate the gross and surplus potential which are discussed below [23,24].

2.2.1. Gross residue potential

Gross residue potential of a particular crop depends upon three parameters *viz*. (i) area covered by the crop (ii) yield of the crop, and (iii) RPR value of the crop. Using these parameters, gross residue potential is estimated as follows:

$$CRg(j) = \sum_{i=1}^{n} A(i,j) \times Y(i,j) \times RPR(i,j) \quad (1)$$

where, $CR_g(j)$ is gross crop residue potential at jth state from n number of crops, tonne; $A(i,j)$ is area under ith crop at jth state, ha; $Y(i,j)$is yield of ith crop at jth state, tonne ha^{-1} and $RPR(i,j)$ is residue production ratio of ith crop at jth state. Spatial variations of yield and RPR within a state are ignored. The values of area and yield are taken from crop statistics data as stated earlier. Standard reports are considered for RPR values as given in Table 1.

2.2.2. Surplus residue potential

Eq. (1) gives only gross residue potential. However, crop residues have competing uses and therefore, only a certain portion of gross residue is available for energy purpose. This portion is termed as surplus and estimated as follows.

$$CRs(j) = \sum_{i=1}^{n} CRg(i,j) \times SF(i,j) \quad (2)$$

where, $CR_s(j)$ is surplus residue potential at jth state from n number of crops, tonne; $CR_g(i,j)$ is gross crop residue potential of ith crop at jth state, tonne and $SF(i,j)$ is surplus residue fraction of ith crop at jth state.

In this study, data available from Biomass Resource Atlas of India (BRAI) is used to estimate surplus residue fraction *i.e*., $SF(i,j)$ [25]. Limited literatures are available on state and crop wise surplus residue potential in India except for few states. Therefore, BRAI reported values of gross and surplus residue are used in this study to estimate surplus residue fraction both at state and crop level. The BRAI databank is available up to the year 2004 only. Hence the present study used 2004 BRAI data because of non-availability of recent data sources. However, in some instances, residue availability data for a particular crop or state is even missing in the BRAI. For example, in case of bajra crop, residue potential is not reported for nine states of India. In such situations, for a particular crop, average of residue values of the reported states is considered for the non-reported states.

2.3. Estimation of bioenergy potential

Bioenergy potential from crop residue biomass is estimated using the following expression:

$$E(j) = \sum_{i=1}^{n} CRs(i,j) \times HV(i,j) \quad (3)$$

where, $E(j)$ is bioenergy potential of n crops at jth state, MJ; $CRs(i,j)$ is surplus residue potential of ith crop at jth state, tonne; $HV(i,j)$ is heating value of ith crop at jth state, MJ tonne^{-1}.

Ignoring the spatial variation, heating values of residues considered in this study are taken from standard sources as indicated in Table 1.

3. Results and discussions

3.1. Crop residue biomass and bioenergy potential

3.1.1. National level potential

It is estimated that, 686 MT gross residue is available in India on annual basis from 39 crop residues generated by 26 crops. Out of this, 545 MT is contributed by cereals, oilseed, pulses and sugarcane crops together; 61 MT by horticultural crops (coconut, banana and areca nut) and 80 MT by others (cotton and jute). At crop group level, cereal contributes the highest amount of 368 MT (54%) followed by sugarcane 111 MT (16%). At individual crop level, rice contributes the highest amount of 154 MT gross residue followed by wheat (131 MT).

Considering the surplus portions of residues available from the selected crops, annual national potential is only 234 MT, *i.e*. 34%

Table 1
RPR and heating values of crop residues.

Crop group	Crop	Residue	RPR	Heating value, MJ/kg	Reference
Cereal	Rice	Straw	1.5	15.54	[24]
		Husk	0.2	15.54	[19]
	Wheat	Stalk	1.5	17.15	[19]
		Pod	0.3	17.39	[19]
	Maize	Cob	0.3	17.39	[19]
		Stalk	2	16.67	[19]
	Bajra	Cob[a]	0.33	17.39	–
		Husk	0.3	17.48	[53]
		Stalk	2	18.16	[54]
	Barley	Straw	1.3	18.16	[54]
	Small millet	Straw	1.2	18.16	[54]
	Ragi	Straw	1.3	18.16	[54]
	Jowar	Cob[b]	0.5	17.39	–
		Husk	0.2	17.48	[53]
		Stalk	1.7	18.16	[54]
Oilseeds	Mustard and rapeseed	Stalk	1.8	17	[19]
	Sesame	Stalk	1.2	14.35	[57]
	Linseed	Stalk	1.47	14.35	[c]
	Niger	Stalk	1	14.35	[d]
	Safflower	Stalk	3	13.9	[e]
	Soybean	Stalk	1.7	16.99	[55]
	Groundnut	Shell	0.3	15.56	[56]
		Stalk	2	14.4	[56]
	Sunflower	Stalk[f]	3	17.53	[57]
Pulses	Tur (arhar)	Stalk	2.5	18.58	[19]
	Lentil	Stalk	1.8	14.65	[58]
	Gaur	Stalk	2	16.02	[19]
	Gram	Stalk	1.1	16.02	[19]
Sugarcane	Sugar cane	Bagasse	0.33	20	[19]
		Top and leaves	0.05	20	[19]
Horticulture	Banana	Peel	3	17.4	[59]
	Coconut	Frond[g]	4	10	[60]
		Husk	0.53	19.4	[61]
	Arecanut	Frond[h]	3	18.1	[i]
		Husk	0.8	17.9	[62]
Others	Cotton	Stalk[j]	3.8	17.4	[56]
		Husk	1.1	16.7	[63]
		Boll shell	1.1	18.3	[64]
	Jute	Stalk	2	19.7	[65]

All the RPR (residue production ratio) values are from [25].
[a, b] Heating value of bajra and jowar cob is taken same as maize cob.
[c, d] Heating value of linseed and niger stalk is taken same as sesame stalk.
[e] Heating value of Safflower is taken same as sunflower.
[f] RPR value of sunflower stalk is taken same as safflower stalk.
[g, h, j] RPR value of coconut frond, areca nut frond and cotton stalks are in tonne/ha.
[i] Heating value of arecanut frond is taken same as coconut frond.

gross residue is available as surplus. Cereals group contribute the highest amount of surplus residue (89 MT) followed by sugarcane (56 MT), others (47 MT), horticultural (23 MT), oilseeds (14 MT) and pulses (5 MT). At individual crop level, maximum amount of surplus residue is contributed by sugarcane (56 MT), followed by cotton (47 MT) and rice (43 MT). Although rice produces the highest amount of gross residue among all the crops, its surplus residue production is less than sugarcane. This is because rice residues (husk and straw) has more competing uses (cattle feed, animal feed, packing material, heating and cooking fuel) than sugarcane (bagasse, leaves and tops). Surplus residue potential from banana and coconut (horticultural crops) is also significant in India and is estimated as 12 MT and 10 MT, respectively. National level gross and surplus residue potential from the selected crops is presented in Table 2.

It is observed that findings of the present study vary with earlier findings. For example, Ravindranath et. al. [26] reported a gross crop residue biomass production of 626.5 MT during the year 1996–97 with a projection of increase up to 840 MT by 2010. On the other hand, Baruah and Jain [27] reported crop residue potential of 540 MT in 1998. According to Purohit [28] 74 MT of crop residue could be utilized for energy generation on annual basis. Singh and Gu [29] reported a gross potential of 1055 MT per year including residues from spice and plantation crops such as rubber and coffee. Tripathi et. al. [30] reported a residue potential of nearly 84 MT for the year 2000–01, however they considered only 8 crop residues *viz. arhar* stalk, maize stalk, maize cob, cotton stalk, mustard stalk, jute and mesta stalk, rice husk and ground nut shell. Considering rice straw alone, it is reported that more than 22 MT straw is available as surplus annually in India [31]. As

Table 2
Gross and surplus crop residue biomass potential in India.

Crop group	Crop	Gross potential, MT	Surplus potential, MT
Cereals	Rice	154.0	43.5
	Wheat	131.1	28.4
	Maize	35.8	9.0
	Bajra	24.3	5.1
	Barley	1.6	0.2
	Small millet	0.6	0.1
	Ragi	2.7	0.3
	Jowar	17.6	3.5
Oilseeds	Mustard and rapeseed	12.7	4.9
	Sesame	0.8	0.1
	Linseed	0.3	0.0
	Niger	0.1	0.0
	Safflower	0.6	0.5
	Soybean	13.5	4.6
	Groundnut	17.0	3.0
	Sunflower	3.8	0.6
Pulses	Tur (arhar)	7.2	1.4
	Gaur	2.6	1.8
	Gram	6.4	1.6
	Lentil	1.7	0.3
Sugarcane	Sugarcane	110.6	55.7
Horticulture	Banana	41.9	12.3
	Coconut	18.0	9.7
	Arecanut	1.5	0.5
Others	Cotton	75.9	46.9
	Jute	3.9	0.4
Total, MT		686.0	234.5

per the MNRE [5], about 120 to 150 MT crop and forestry residues are available as surplus for energy generation in India, equivalent to 18 GW power potential. The variations in estimations could be due differences in consideration of crop types, RPR and heating values, and surplus residue fraction. For example, Singh and Gu [29], in their study, included residues from spice crops (ginger, cardamom, coriander, garlic, cumin, and dry chilly) and rubber while the present study and Ravindranath et. al. [26] did not include these residues. Considering the data gap and differences in estimation procedure, Sukumaran et. al. [32] also reported that precise estimate of biomass availability in India is non-existent and the only statistics that available are on crop production and of forest coverage. Furthermore they also remarked that even when biomass resources are documented, there seems to be inconsistencies in data between different agencies, and the statistics are often not complete or transparent. However, the present study attempted to overcome many of these weaknesses to evolve reasonably accurate estimate.

Bioenergy potential from the surplus portion of residue in the country would be 4.15 EJ per annum. This is approx. 17% of primary energy consumption in India (as per the estimation of IEA in 2011 [33], total primary energy consumption in India is about 24.91 EJ). Cereals contributes 1.49 EJ followed by sugarcane (1.11 EJ), others (0.83 EJ), horticultural (0.41 EJ), oilseed (0.23 EJ) and pulses (0.08 EJ). At individual crop level, the highest contribution comes from sugarcane residue (1.11 EJ).

3.1.2. State level potential

Residue potential varies significantly among the states of India. In terms of gross potential, it ranges from a minimum value 0.21 MT in Mizoram to maximum value of 121 MT in Uttar Pradesh. Uttar Pradesh is one of the agriculturally advanced states of India. Sugarcane is widely cultivated in the state followed by wheat and rice. Together these three crops contributes more than 90% residue generated in the state. Punjab, another agriculturally advanced state of India, produces 83 MT gross residues annually.

Concerning the surplus residue potential, Uttar Pradesh produces the highest amount (40 MT) followed by Maharashtra (31 MT) and Punjab (28 MT). Crop group wise surplus residue potential for all the states of India are presented in Fig. 1.

State wise variation in bioenergy potential from surplus residue ranges from 0.84 PJ in Mizoram to 743.15 PJ in Uttar Pradesh (Fig. 2). The variations in cropped area, cropping pattern, yield, surplus fraction of residue are some of the major factors resulting variation in surplus residue potential and hence related bioenergy potential amongst the states. Maharashtra (563 PJ), Punjab (467 PJ), Gujarat (426 PJ), Tamil Nadu (317 PJ), Rajasthan (200 PJ), Haryana (292 PJ), and Madhya Pradesh (207 PJ) are the major surplus residue potential states of India. Among the Northeastern state, Assam has the highest potential of 33 PJ per annum.

Annual per capita crop residue bioenergy potential is also estimated for all the states using Census of India, 2011 population data. Significant variation in per capita bioenergy availability is observed among the states which range from the lowest in West Bengal (679 MJ) to highest in Punjab (16,860 MJ) (Fig. 3). Similar to West Bengal, per capita bioenergy availability in Jharkhand and Mizoram are 688 MJ and 773 MJ, respectively. On the other hand, Punjab is followed by Haryana (11,559 MJ per capita) and Gujarat (6660 MJ per capita). About 3716 MJ crop residue based bioenergy would be available for a person of Uttar Pradesh, the most populous state of India (200 million). In the Northeastern states, the highest potential is found in Nagaland (1966 MJ per capita) followed by Tripura (1548 MJ per capita) and Arunachal Pradesh (1457 MJ per capita). Sikkim, the least populous state with 0.6 million population, have a per capita bioenergy potential of 1428 MJ.

3.2. Competing uses of crop residue biomass in India

Significant variations are observed among the states of India in terms of surplus residue fraction availability as shown in Table 3. Nationally 34% of the gross residue generated is available as surplus. However, at state level the availability varies from a minimum level of 21% in Arunachal Pradesh to a maximum value of 48% in Haryana and Punjab. Uttar Pradesh, which produces the highest amount of residue in the country, has surplus availability of 33%, almost equal to national value but less than many other states.

Biomasses such as fuel wood, animal dung, crop residue are widely used as a source of energy in developing countries. The used pattern of crop residues for fulfilling domestic energy needs is not uniform amongst the regions in India. For example, rural population of Uttarakhand depends primarily on fuelwood as energy for cooking. However, in some other regions of India, where forest resources are not sufficient, people use easily available crop residues and dung cake as energy for cooking. In Uttarakhand, crop residues are mostly used as feed for the livestock. However, rice straw is not preferred as a cattle feed in Punjab, Haryana and Uttar Pradesh [34,35]. The residues are either left uncollected in the field or burnt after grain harvest. Use of rice straw as animal feed is common among the rural households of Assam and West Bengal. Use of wheat straw as animal feed is also reported to be common in the Trans-Gangetic plains to Bihar sub-regions of India [36]. Top of sugarcane is also used as animal feed in

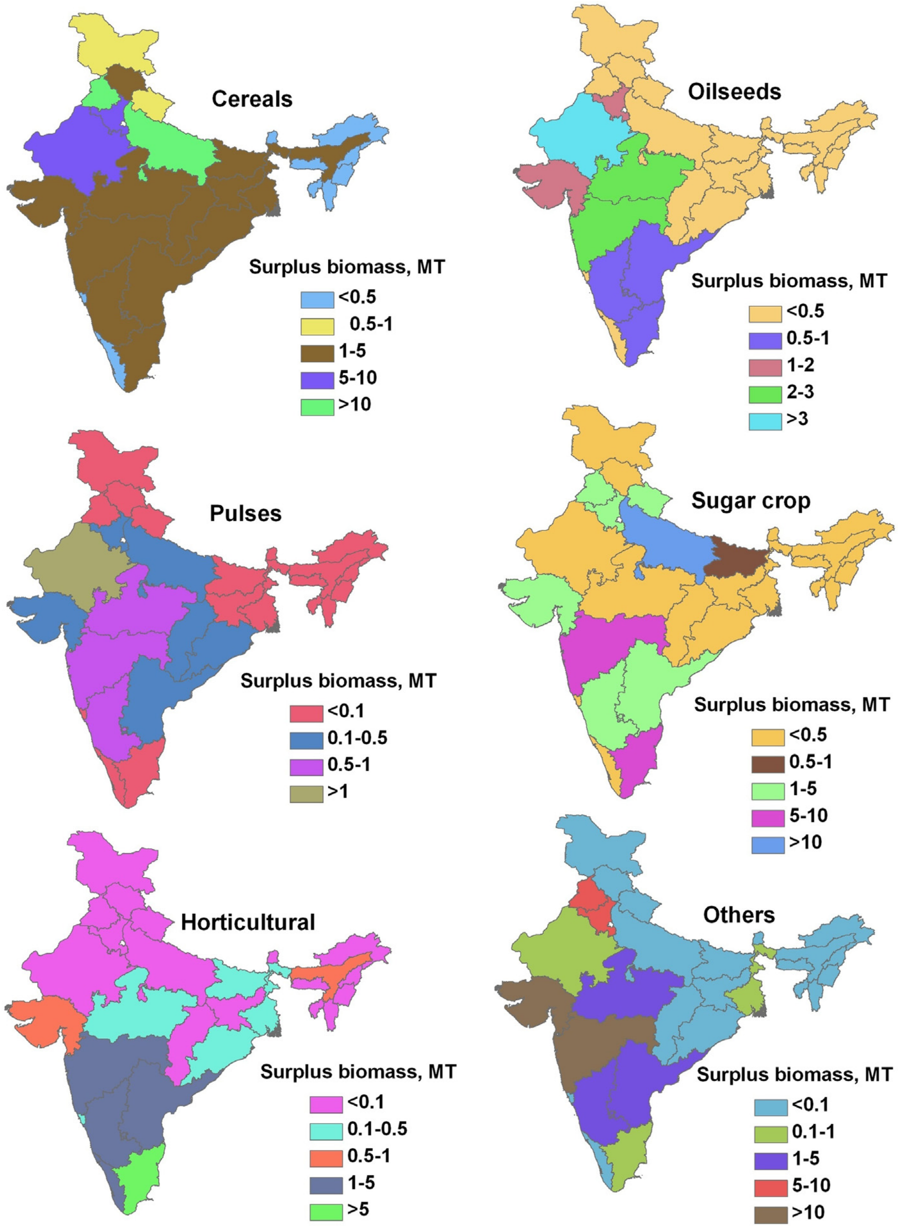


Fig. 1. State wise surplus crop residue biomass potential in India.

some states. Burning of the cereal residue is prominent over northwest and central Uttar Pradesh, whereas rice straw burning is limited and wheat straw burning is almost absent. Beri et. al. [37] estimated that 22% of rice straw and 10% of wheat straw are burned *in-situ* in Uttar Pradesh. In Bihar, the uses of crop residues like rice straw; wheat straw and gram as fuels are limited. Wheat straw is relatively sturdy and its use as animal feed becomes possible due to mechanical threshing that now prevails in the wheat-growing areas [36]. Mechanical threshing chops the wheat straw into *bhusa* (small pieces which are more palatable). The use of maize residue and other crops varies over the regions but also provide important feed sources. Chauhan [38] reported that out of the 25 MT crop residues generated annually in the state of Haryana, 71% is consumed in various domestic and commercial activities within the state. Citing a rural area of Haryana, Joon et al. [39] reported that more than 80% of rural households use wood, dung, crop residue or all of them along with LPG, while 48% of household use dung cake and crop residue for water heating purpose.

3.3. *Major issues associated with the uses of crop residue biomass*

Nutrient recycling in the soil–plant ecosystem is an essential component of sustainable productive crop enterprise. Incorporation of crop residues improves soil environment, which influences the microbial population and activity in the soil and subsequent nutrient transformations [40]. Thus, indiscriminate removal of crop residues can adversely impact soil properties, soil organic matter (SOM) dynamics, water and wind erosion and crop production [41]. However, Blanco-Canquia and Lal [40] remarked that a fraction of the crop residue produced may be available for removal from soils. It is further reported that adverse changes occur only after excessive or complete residue removal. In certain cases changes due to crop residue removal are found insignificant. The authors also cited some studies suggesting that about 30% to 50% corn stover, especially in the US Corn Belt region can be removed for alternative uses without causing severe negative impacts on soil [42–45]. However it is still uncertain where, when and how

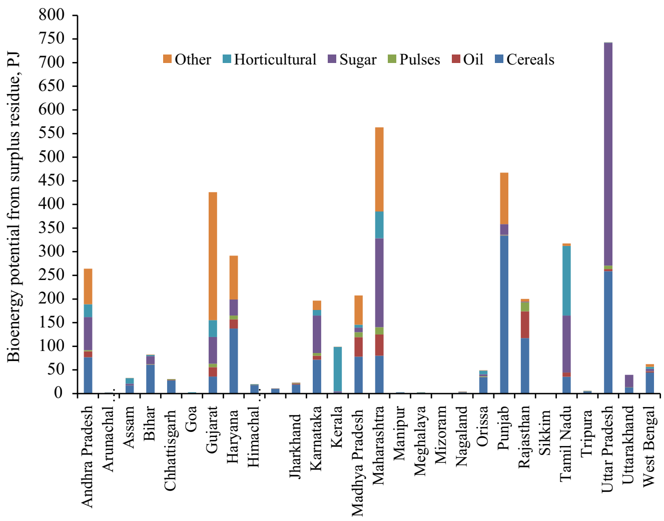


Fig. 2. State wise crop residue bioenergy potential in India.

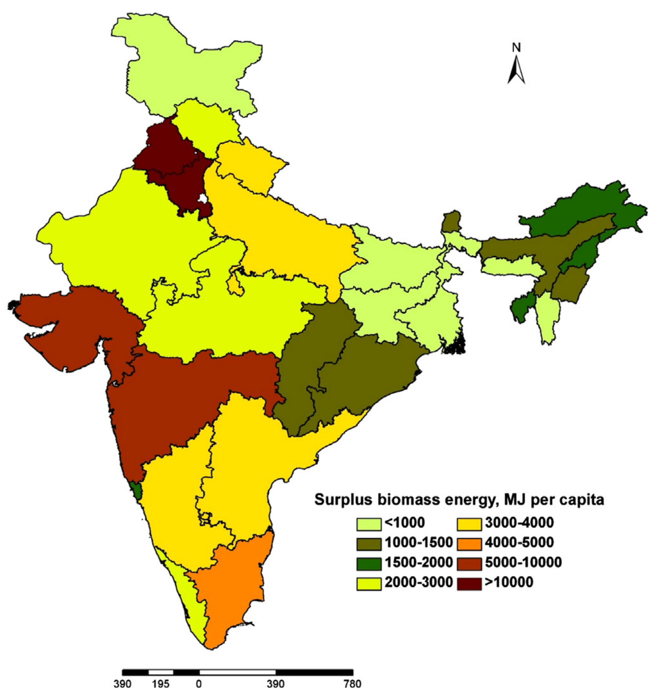


Fig. 3. State wise per capita crop residue bioenergy potential in India.

much residue can be removed sustainably (Ref. [46] cited in Ref. [40]).

The crop residue generated in the field has to be made available to the user facilities. The supply chain involves collection, storage and transportation of residue from field to user site. All these processes influence the resulting feedstock cost. The bulky nature or low energy density of agricultural residues possesses problems in handling, storage, transportation and conversion processes. Densification increases energy density of biomass and also makes transportation and storage economical. Biomass densification can be done *via* two processes (i) mechanical (*e.g.* bales, pellets, cubes, and briquettes) and (ii) pyrolysis (*e.g.* torrefaction, slow pyrolysis, and fast pyrolysis) [47]. Appropriateness of the processes is to be judged based on the situation specific consideration.

Harvesting and transportation costs are major components of crop residue based bioenergy planning. Prevailing practices of harvesting vis-à-vis scope for introducing mechanical methods of harvesting also influence the viability of crop residue based power project. Again, biomass transportation cost is a function of the quantity of available biomass in a region and the transportation distance [48]. Therefore, it is desirable to ensure availability of adequate crop residue in the vicinity of power plant location.

Use of Geographical Information System (GIS) tools is found to be used for investigation of power plant location, cost effective transportation network to minimize the overall cost of biomass feedstock [48,49]. In a recent study, Hiloidhari et al. [49] estimated the cost of rice straw production, harvest and transportation using GIS. Incorporating all the three cost parameters (production, harvest and transportation), they estimated the overall cost of rice straw as approx. $25 t^{-1}. Further, the authors have also mentioned that manual harvest of residue is predominant in several parts of India.

Crop residue fuel characteristics including moisture content would influence the decision of appropriate conversion route. In general, thermal conversion of biomass requires low moisture content (less 50%) while bio-conversion can utilize high moisture feedstock. Thermal conversion technologies can also use high moisture content feedstocks but the overall energy balance for the conversion process is adversely impacted [50]. Moisture in biomass fuel reduces the heating value, thus if too much moisture is present, the fuel will not spontaneously react [51]. Moisture content of herbaceous and agricultural vary from about 9% to 35% depending on the plant species [52].

Thus, it is seen that there are several important issues concerning the bioenergy utilization of crop residues *viz*., (i) soil health, (ii) practices of collection, handling and storage, (iii) appropriate technology of conversion suiting fuel characteristics, and (iv) economy of fuel substitution which are expected to vary amongst the states of India. The potential estimates of the present investigation would require to be considered keeping in mind of such varying dynamics.

4. Conclusions

The present study estimated crop residue biomass and subsequently bioenergy potential of 39 residues from 26 crops for all the 28 states of India. Rice, sugarcane, wheat and cotton are the major contributor to India's crop residue biomass pool. Overall, the country produces 686 MT gross residue annually, of which 234 MT (34% of gross) available as surplus. Uttar Pradesh produces the highest amount of surplus residue in the country (40 MT). Ten states *viz*. Uttar Pradesh, Maharashtra, Punjab, Gujarat, Tamil Nadu, Haryana, Andhra Pradesh, Karnataka, Madhya Pradesh and Rajasthan, together contribute 89% of India's surplus residue generation. Nationally, annual bioenergy potential from the surplus residue is 4.15 EJ, equivalent to 17% of India's total primary energy consumption. State wise variation in bioenergy potential from surplus residue ranges from a minimum value of 0.84 PJ in Mizoram to a maximum value of 743.15 PJ in Uttar Pradesh. In terms of per capita bioenergy potential from the surplus crop residue, it varies from 679 MJ in West Bengal to 16,840 MJ in Punjab.

The present study is challenged by two important data limitation. First, state wise spatial variation in residue production ratio (RPR) and heating values of crop residues could not be directly determined. Although these values are based on standard literatures but they are not available. Second, spatial variation in competing uses of crop residues among the states also could not be directly determined. Addressing these issues would result in precise assessment of India's crop residue based bioenergy potential.

Table 3
State wise surplus fraction of residue availability (% of gross).

State	Cereals	Oilseeds	Sugarcane	Horticulture	Pulses	Others	State avg.
Andhra Pradesh	29	26	40	44	23	38	33
Arunachal Pradesh	27	11	33	25	22	10	21
Assam	25	40	40	45	47	48	41
Bihar	27	32	33	20	23	10	24
Chhattisgarh	29	20	40	25	47	38	33
Goa	26	NA	38	39	NA	70	43
Gujarat	30	25	40	47	53	NA	39
Haryana	34	37	40	NA	40	90	48
Himachal Pradesh	35	17	38	25	35	48	33
Jammu & Kashmir	29	17	40	NA	NA	NA	29
Jharkhand	26	33	40	NA	47	10	31
Karnataka	30	31	38	32	47	33	35
Kerala	30	20	68	38	35	10	32
Madhya Pradesh	28	23	40	25	43	70	38
Maharashtra	28	33	33	43	47	40	37
Manipur	28	21	40	25	NA	NA	29
Meghalaya	26	15	40	20	35	30	28
Mizoram	29	18	40	32	35	48	34
Nagaland	27	16	40	43	35	38	33
Orissa	29	29	33	52	40	10	32
Punjab	34	30	40	NA	47	90	48
Rajasthan	29	18	40	NA	23	10	24
Sikkim	28	22	NA	NA	NA	NA	25
Tamil Nadu	33	19	40	48	30	29	33
Tripura	34	21	40	45	35	38	37
Uttar Pradesh	37	23	38	25	25	48	33
Uttarakhand	32	53	38	NA	55	NA	43
West Bengal	24	20	43	50	29	30	29
National avg.	29	30	39	42	38	38	34

The residue production potential is reflected by the share of cropped area and related productivity. It is well known fact that there exist variations among the Indian states pertaining to the above factors. The present study also reveals that crop residue potential and hence bioenergy potential in all the eight North-eastern states is much lower than rest of the country. Except Assam, the potential is almost negligible in other Northeastern states.

It is expected that state as well as well crop level bioenergy potential assessment made in this study will help in policy decisions and regional bioenergy planning of the country.

Acknowledgment

The first author is thankful to the Council of Scientific and Industrial Research, Govt. of India for providing financial assistance in terms of Senior Research Fellowship. The first author is also thankful to the J. William Fulbright Foreign Scholarship Board (FFSB), Washington, DC for awarding 2013–14 Fulbright-Nehru Doctoral and Professional Research Fellowship for research study at University of California, Davis.

References

[1] India, Biomass for Sustainable Development-Lessons for Decentralized Energy Delivery Village Energy Security Programme. Document of the World Bank. 2011. ⟨http://www.mnre.gov.in/pdf/VESP-Final-Report-July%202011.pdf⟩.
[2] Kumar U, Jain VK. Time series models (Grey-Markov, Grey Model with rolling mechanism and singular spectrum analysis) to forecast energy consumption in India. Energy 2010;35:1709–16.
[3] Basic Statistics on Indian Petroleum & Natural Gas, 2009–10. Ministry of Petroleum & Natural Gas, Government of India. ⟨http://petroleum.nic.in/petstat.pdf⟩. [accessed November 2011].
[4] Ailawadi VS, Bhattacharyya SC. Access to energy services by the poor in India: current situation and need for alternative strategies. Nat Resour Forum 2006;30:2–14.
[5] Annual report 2010–11. Ministry of New and Renewable Energy. ⟨http://www.mnre.gov.in/annualreport/2010_11_English/index.htm⟩ [accessed December 2011].
[6] Bhattacharyya SC. Energy access problem of the poor in India: Is rural electrification a remedy? Energy Policy 2006;34:3387–97.
[7] Pachauri S, Jiang L. The household energy transition in India and China. Energy Policy 2008;36:4022–35.
[8] Kishore VVN, Bhandari PM, Gupta P. Biomass energy technologies for rural infrastructure and village power – opportunities and challenges in the context of global climate change concerns. Energy Policy 2004;32:801–10.
[9] Ekholm T, Krey V, Pachauri S, Riahi K. Determinants of household energy consumption in India. Energy Policy 2010;38:5696–707.
[10] Balachandra P. Modern energy access to all in rural India: an integrated implementation strategy. Energy Policy 2011;39:7803–14.
[11] Patel SR, Bhoi PR, Sharma AM. Field-testing of SPRERI's open core gasifier for thermal application. Biomass Bioenergy 2006;30:580–3.
[12] Kapur T, Kandpal TC, Garg HP. Electricity generation from rice husk in Indian rice mills: potential and financial viability. Biomass Bioenergy 1998;14:573–83.
[13] Singh RN, Jena U, Patel JB, Sharma AM. Feasibility study of cashew nut shells as an open core gasifier feedstock. Renewable Energy 2006;31:481–7.
[14] Palit D, Mande S. Biomass gasifier systems for thermal applications in rural areas. Boiling Point 2007;53:17–9.
[15] Jorapur R, Rajvanshi AK. Sugarcane leaf bagasse gasifiers for industrial heating applications. Biomass Bioenergy 1995;8:91–8.
[16] Dasappa S, Subbukrishna DN, Suresh KC, Paul PJ, Prabhu GS. Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India. Energy Sustain Dev 2011;15:231–9.
[17] ⟨http://data.worldbank.org/indicator/AG.LND.AGRI.ZS/countries⟩. [Access 01.11.13].
[18] Baruah DC, Hiloidhari M. Adequacy of crop residue biomass as renewable energy for tea drying in Assam: a spatial assessment. J Crop Eng 2009;46:43–50.
[19] Singh J, Panesar BS, Sharma SK. Energy potential through crop biomass using geographical information system – a case study of Punjab. Biomass Bioenergy 2008;32:301–7.
[20] Das S, Jash T. District-level biomass resource assessment: a case study of an Indian State West Bengal. Biomass Bioenergy 2009;33:137–43.
[21] Chauhan S. Biomass resources assessment for power generation: a case study from Haryana state, India. Biomass Bioenergy 2010;34:1300–8.
[22] Directorate of Economics and Statistics, Ministry of Agriculture, Govt. of India. Agriculture Statistics at a glance 2010. ⟨http://agricoop.nic.in/Agristatistics.htm⟩ [accessed August 2011].
[23] Hiloidhari M, Baruah DC. Crop residue biomass for decentralized electrical power generation in rural areas (part 1): investigation of spatial availability. Renew Sustain Energy Rev 2011;15:1885–92.

[24] Hiloidhari M, Baruah DC. Rice straw residue biomass potential for decentralized electricity generation: a GIS based study in Lakhimpur district of Assam, India. Energy Sustain Dev 2011;15:214–22.
[25] Biomass Atlas V2.0. Biomass Resource Atlas of India. ⟨http://lab.cgpl.iisc.ernet.in/Atlas/⟩ [accessed October 2011].
[26] Ravindranath NH, Somashekar HI, Nagaraja MS, Sudha P, Sangeetha G, Bhattacharya SC, et al. Assessment of sustainable non-plantation biomass resources potential for energy in India. Biomass Bioenergy 2005;29:178–90.
[27] Baruah DC, Jain AK. Distribution of crop crop residues in India. J Crop Eng 1998;25:7.
[28] Purohit P. Economic potential of biomass gasification projects under clean development mechanism in India. J Clean Prod 2009;17:181–93.
[29] Singh J, Gu S. Biomass conversion to energy in India–A critique. Renew Sustain Energy Rev 2010;14:1367–78.
[30] Tripathi AK, Iyer PVR, Kandpal TC, Singh KK. Assessment of availability and costs of some crop residues used as feedstocks for biomass gasification and briquetting in India. Energy Convers Manage 1998;39:1611–8.
[31] Gadde B, Menke C, Wassmann R. Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass Bioenergy 2009;33:1532–46.
[32] Sukumaran RK, Surender VJ, Sindhu R, Binod P, Janu KU, Sajna KV, et al. Lignocellulosic ethanol in India: prospects, challenges and feedstock availability. Bioresour. Technol. 2010;101:4826–33.
[33] ⟨http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=44&aid=2&cid=IN,&syid=2008&eyid=2012&unit=QBTU#⟩. [accessed 12.11.13].
[34] Asadullah M, Rahman MA, Ali MM, Motin MA, Sultan MB, Alam MR, et al. Jute stick pyrolysis for bio-oil production in fluidized bed reactor. Bioresour. Technol. 2008;99:44–50.
[35] Devendra C, Thomas D. Crop–animal interactions in mixed farming systems in Asia. Crop Syst 2002;71:27–40.
[36] Saud T, Singh DP, Mandal TK, Ranu Gadi, Pathak H, Saxena M, et al. Spatial distribution of biomass consumption as energy in rural areas of the Indo-Gangetic plain. Biomass Bioenergy 2011;35:932–41.
[37] Beri V, Sidhu BS, Gupta AP, Tiwari RC, Pareek RP, Rupela OP, et al. Organic resources of a part of Indo-Gangetic Plain and their utilization. Ludhiana: Department of Soils, Punjab Crop University; 2003 (National Crop Technology Project (NATP).
[38] Chauhan S. Biomass resources assessment for power generation: A case study from Haryana state, India. Biomass Bioenergy 2010;34:1300–8.
[39] Joon V, Chandra A, Bhattacharya M. Household energy consumption pattern and socio-cultural dimensions associated with it: a case study of rural Haryana, India. Biomass Bioenergy 2009;33:1509–12.
[40] Blanco-Canqui H, Lal R. Crop residue removal impacts on soil productivity and environmental quality. Crit Rev Plant Sci 2009;28:139–63.
[41] Kludze H, Deena B, Weersink A, van Acker R, Janovicek K, Laporte AD, et al. Estimating sustainable crop residue removal rates and costs based on soil organic matter dynamics and rotational complexity. Biomass Bioenergy 2013;56:607–18.
[42] Lindstrom MJ, Skidmore EL, Gupta SC, Onstad A. Soil conservation limitations on removal of crop residues for energy production. J Environ Qual 1979;8:533–7.
[43] Nelson RG. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States – rainfall and wind-induced soil erosion methodology. Biomass Bioenergy 2002;22:349–63.
[44] Kim S, Dale BE. Global potential bioethanol production from wasted crops and crop residues. Biomass Bioenergy 2004;26:361–75.
[45] Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL. Current and potential U.S. corn stover supplies. Agron J 2007;99:1–11.
[46] Wilhelm WW, Johnson JMF, Karlen D, Lightle D. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 2007;99:1665–7.
[47] ⟨http://www.omafra.gov.on.ca/english/engineer/facts/11-035.htm#6⟩. [accessed 11.11.13].
[48] Voivontas D, Assimacopoulos D, Koukios EG. Assessment of biomass potential for power production: a GIS based method. Biomass Bioenergy 2001;20:101–12.
[49] Hiloidhari M, Baruah D, Mahilary H, Baruah DC. GIS based assessment of rice (Oryza sativa) straw biomass as an alternative fuel for tea (*Camellia sinensis* L.) drying in Sonitpur district of Assam, India. Biomass Bioenergy 2012;44:160–7.
[50] McKendry P. Energy production from biomass (Part 1): overview of biomass. Bioresour. Technol. 2002;83:37–46.
[51] Jenkins BM, Baxter LL, Miles Jr TR, Miles TR. Combustion properties of biomass. Fuel Process Technol 1998;54:17–46.
[52] Vassilev SV, Baxter D, Andersen LK, Vassileva CG. An overview of the chemical composition of biomass. Fuel 2010;89:913–33.
[53] Raveendran K, Ganesh A, Khilar C. Influence of mineral matter on biomass pyrolysis characteristics. Fuel 1995;74:1812–22.
[54] Friedl A, Padouvas E, Rotter H, Varmuza K. Prediction of heating values of biomass fuel from elemental composition. Anal Chim Acta 2005;544:191–8.
[55] Kiš D, Sučić B, Guberac V, Voća N, Rozman V, Šumanovac L. Soybean biomass as a renewable energy resource. Agric Conspec Sci 2009;74:201–3.
[56] Jekayinfa SO, Scholz V. Potential availability of energetically usable crop residues in Nigeria. Energy Sources, Part A: Recovery, Utilization Environ Effects 2009;31:687–97.
[57] Zabaniotou A, Ioannidou O, Antonakou E, Lappas A. Experimental study of pyrolysis for potential energy, hydrogen and carbon material production from lignocellulosic biomass. Int J Hydrogen Energy 2008;33:2433–44.
[58] Calorific values–CDM. ⟨http://cdm.unfccc.int/.../ZKN42U16X8VOJIAG5MW7T3CFPRBDS9⟩.
[59] Wilaipon P. The effects of briquetting pressure on banana-peel briquette and the banana waste in Northern Thailand. Am J App Sci 2009;6:167–71.
[60] Rahman MdT. Green energy development model in the St. Martin's Island and energy from coconut palm biomass, ISBN:984-8323-02-3, 1st ed. July, 2006.
[61] Minowa T, Kondo T, Sudirjo ST. Thermochemical liquefaction of Indonesian biomass residues. Biomass Bioenergy 1998;14:517–24.
[62] Pilon G. Utilization of Arecanut (*Areca catechu*) husk for gasification. [MSc. thesis]. Department of Bioresource Engineering, McGill University, Montreal; 2007. ⟨http://webpages.mcgill.ca/staff/deptshare/FAES/066-Bioresource/Theses/theses/353GuillaumePilon2007/353GuillaumePilon2007.pdf⟩.
[63] Biomass and biofuels calorific values—Biofuels B2B. ⟨http://www.biofuelsb2b.com/useful_info.php?page=TYPIC⟩.
[64] Çağlar A, Demirbaş A. Conversion of cotton cocoon shell to liquid products by supercritical fluid extraction and low pressure pyrolysis in the presence of alkalis. Energy Convers Manage 2001;42:1095–104.
[65] Asadullah M, Rahman MA, Ali MM, Motin MA, Sultan MB, Alam MR, et al. Jute stick pyrolysis for bio-oil production in fluidized bed reactor. Bioresour Technol 2008;99:44–50.